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# COMBUSTION PROPERTIES OF HIGH-DENSITY FUELS

by
M. Thomas McCall and John M. Brupbacher



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## INTRODUCTION AND SUMMARY

The present investigation has been undertaken with the aim of developing a technique to investigate the combustion of fuel mist in a simulated rocket engine environment. The approach taken consists of the development of the nebulizer-coupled-shock-tube technique and its application to the proposed ASALM fuel, RJ-5. The method (refer to Figure 1) involves using shock induced heating to initiate combustion of fuel air mist in the reflected shock zone and monitoring the burning process using various spectroscopic techniques . The construction details as well as a number of important experimental considerations[2] have previously been discussed.

The project is proceeding on schedule. The entire system is operational and combustion of RJ-5 mist has been observed.

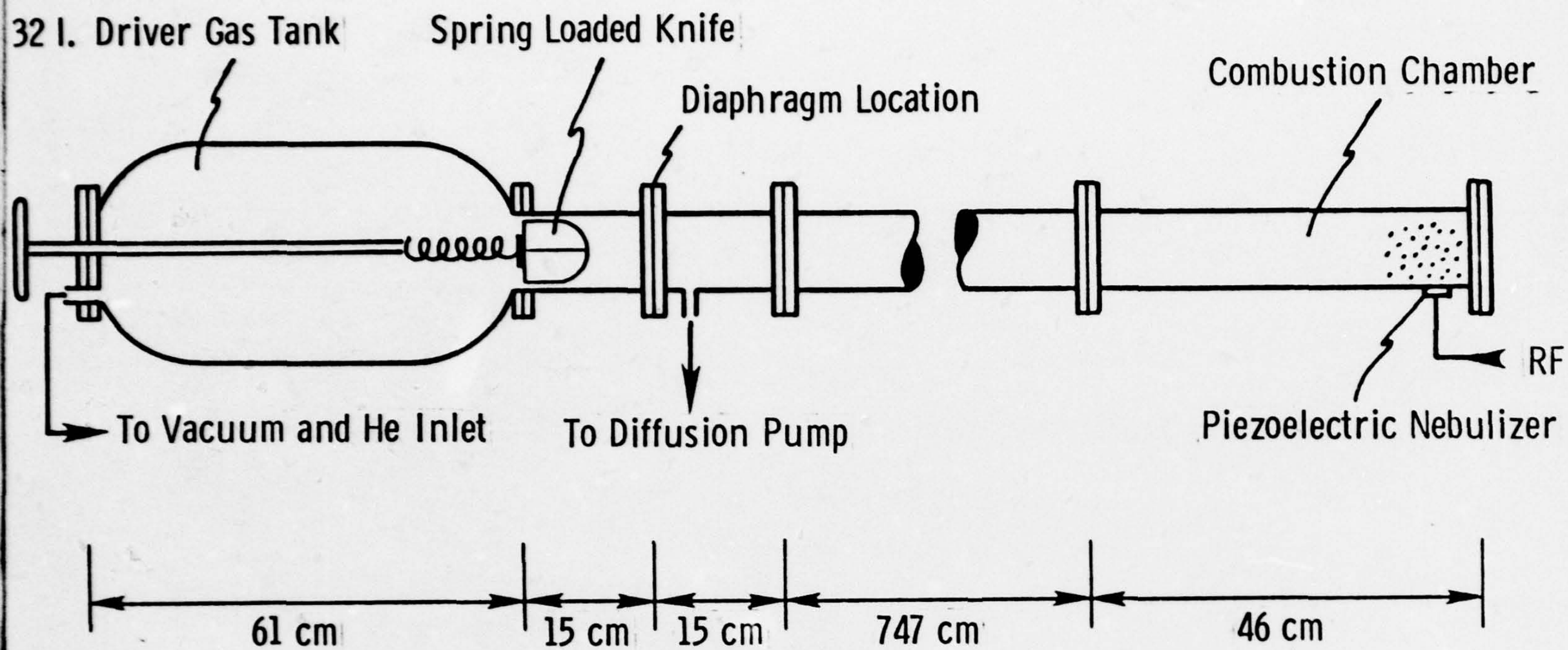



Figure 1. General schematic of nebulizer-coupled-shock-tube.

# RESULTS AND DISCUSSION

## Fuel Nebulization

In ultrasonic nebulizers, the mechanical energy necessary to atomize a liquid comes from a piezoelectric crystal vibrating under the influence of an alternating electric field produced by an electronic high frequency oscillator. Crystal vibrations cause liquid on its surface to break into a fountain of small droplets ultimately leading to a fine mist.

Two important features of the ultrasonic nebulizer technique led to its choice for the present study. Firstly, the particle distribution band is exceptionally narrow; and, secondly, it is tunable over a wide range of droplet diameters. These features make it ideally suited for investigations where the influence of varying particle diameter is of primary concern. In the initial experiments reported herein, a transducer was chosen with a resonance frequency of 1.4 M Hz. The count median particle diameter, $d_{cm}$, can be obtained from the relationship

$$d_{cm} = 0.34\ (8\pi\sigma/\rho\,\omega^2)^{1/3}$$

where $\sigma$ is the solution surface tension, $\rho$ is the density, and $\omega$ is the resonance frequency[3]. For aqueous solutions at 1.4 M Hz this leads to a value of $d_{cm}$ of 3.9 microns. An experimental value of 3.7 microns has been reported, which is in good agreement with this result[4]. For RJ-5, however, the surface tension and density are somewhat different.

Furthermore, the influence of other parameters on the particle size and distribution is not known.

Of particular concern was the viscosity of RJ-5 ($\eta^{0°F} \approx 200$ cs), which is very high compared with that of water ($\eta^{0°F} = 0.80$ cs). Fortunately, however, no such problem materialized*. Small samples of RJ-5 were readily nebulized to yield a fine fuel mist. A microscope slide was passed through the mist and a photograph of the collected mist is seen in Figure 2. Two features are readily apparent. Firstly, the droplets are approximately of the predicted size (ca. 4 μ); and secondly, the size distribution is very narrow, varying only a few microns from the largest to the smallest.

One area in which the literature was deficient concerning ultasonic nebulizers, was the lower liquid volume limit at which they would efficiently operate. In fact, in most reported applications the transducer was entirely submerged under a layer of liquid. This was an area of concern because a successful deployment of the initial shock tube design required the ability to nebulize very small amounts of fuel (<25μℓ). Furthermore, the modifications required to accommodate large liquid volumes would not have been easy to implement. However, experiments show that samples of RJ-5 as small as 0.5 μℓ can be easily nebulized inside the shock tube combustion chamber.

It is noteworthy that even very small amounts of RJ-5 lead to enormous numbers of fuel droplets. For instance, complete nebulization of a 5 μℓ sample of of RJ-5 with an average particle diameter of 5 micron would lead to $8 \times 10^7$ droplets. If these droplets are isolated

* Problems did arise, however, in using the R.F. circuit provided by Denton and given in an earlier report. The corrected circuit will be given in the final project report at a later date.

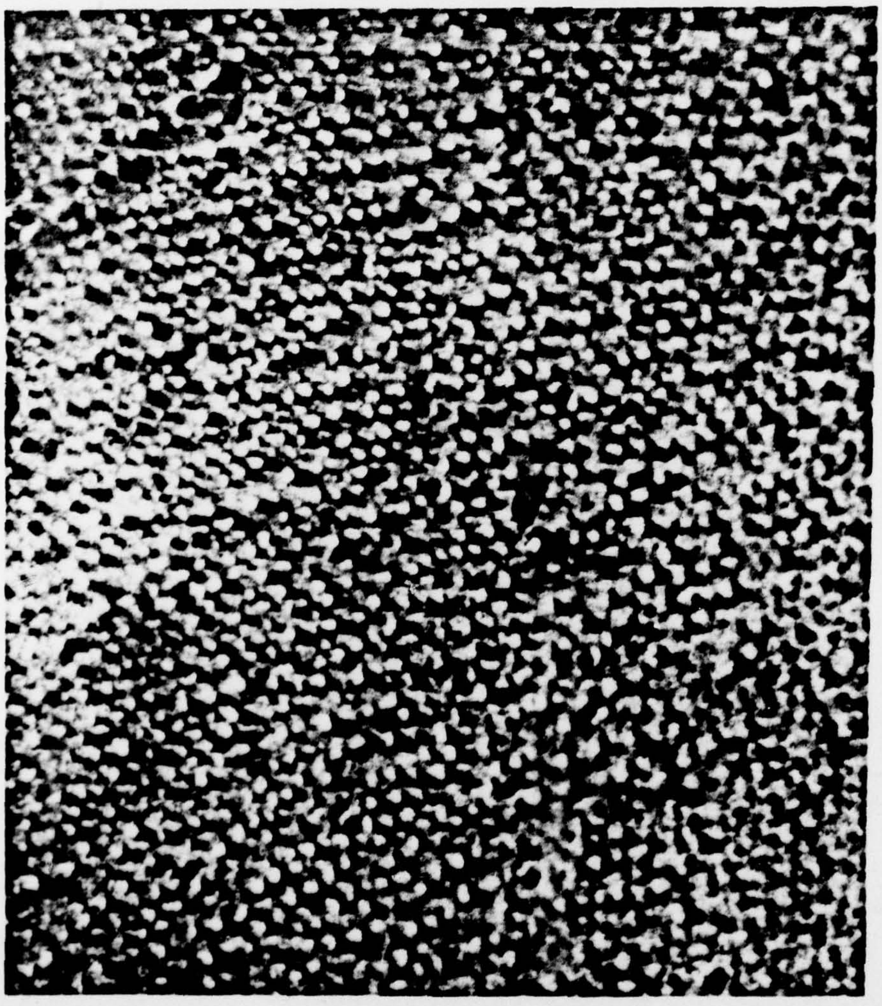


Figure 2. Photograph of RJ-5 droplets generated by ultrasonic nebulizer at 1.4 mHz; 1 mm = 5 microns.

in the last 100 $cm^3$ of the shock tube, the droplet density will be about $10^6$ droplets/$cm^3$.

Nebulization in the shock tube combustion chamber, located at the very end of the shock tube, yielded a mist which appeared to be relatively uniform throughout the last several inches of the shock tube and took about 30 seconds to completely settle. This was verified by performing a Tyndal type experiment in which a narrow beam of light was directed along the shock tube axis. The perpendicularly scattered light from the small droplets was viewed through the side viewing ports as shown in Figure 3. There did not appear to be a[illegible]dency for the droplets to migrate to the shock tube walls or to aggl[illegible]nto larger drops (refer to Figure 2).

<u>Mist Combustion</u>

Having determined that a stable mist of fuel droplets could be successfully generated in the shock tube combustion chamber, we performed a series of experiments in order to demonstrate that heterogeneous fuel combustion was indeed occurring in the shock tube combustion chamber. The results of these experiments are depicted in the series of Polaroid records discussed below.

A preliminary shock wave was initiated into oxygen containing RJ-5 mist. An explosion clearly took place as noted by a loud noise and an intense visible flash (Figure 4) which emanated from the windows of the combustion chamber. An infrared detection system was then coupled to one viewing port. It contained a narrow band filter to selectively monitor emissions from one product of combustion, $CO_2$.

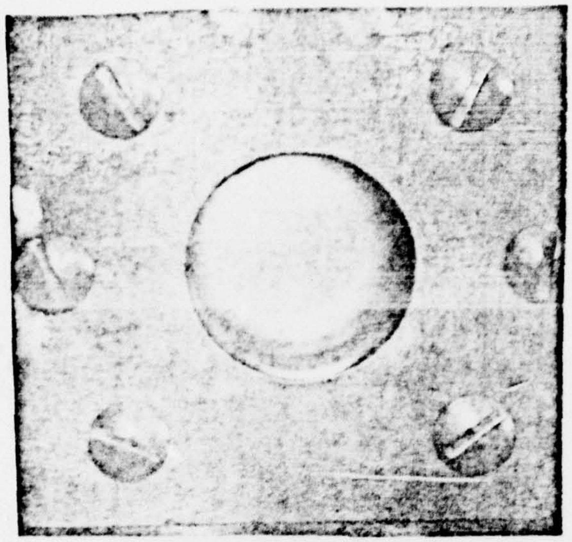


Figure 3a Photograph through viewing port of reflected shock zone. Nebulizer off.

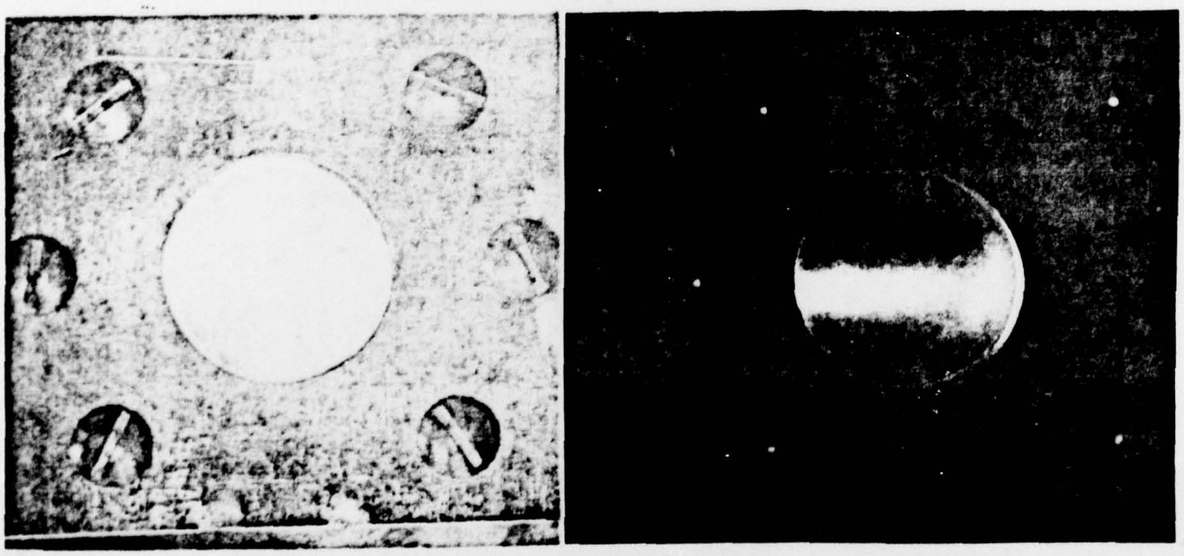


Figure 3b. Photographed while Nebulizing into beam of light introduced from end of shock tube. Photograph at right taken under subdued lighting to demonstrate light scattering by RJ-5 mist.

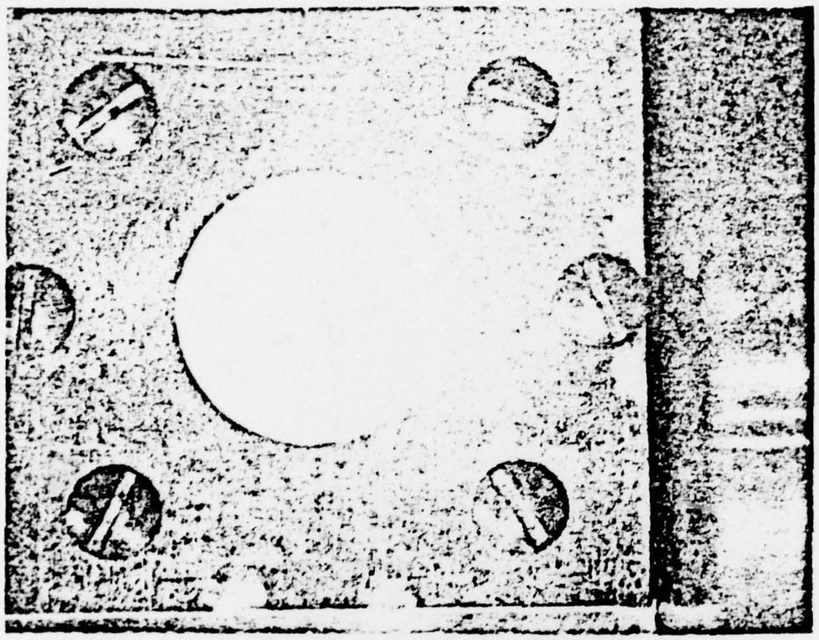


Figure 4: Visible light emitted during combustion experiment is indicated by white central spot.

The opposite viewing port was equipped with a phototube assembly to display the visible emissions during combustion. The signals from these two detectors, along with the signal from a pressure transducer, were simultaneously displayed on an oscilloscope for the remaining experiments. A detailed schematic of these monitoring devices is given in Figure 5.

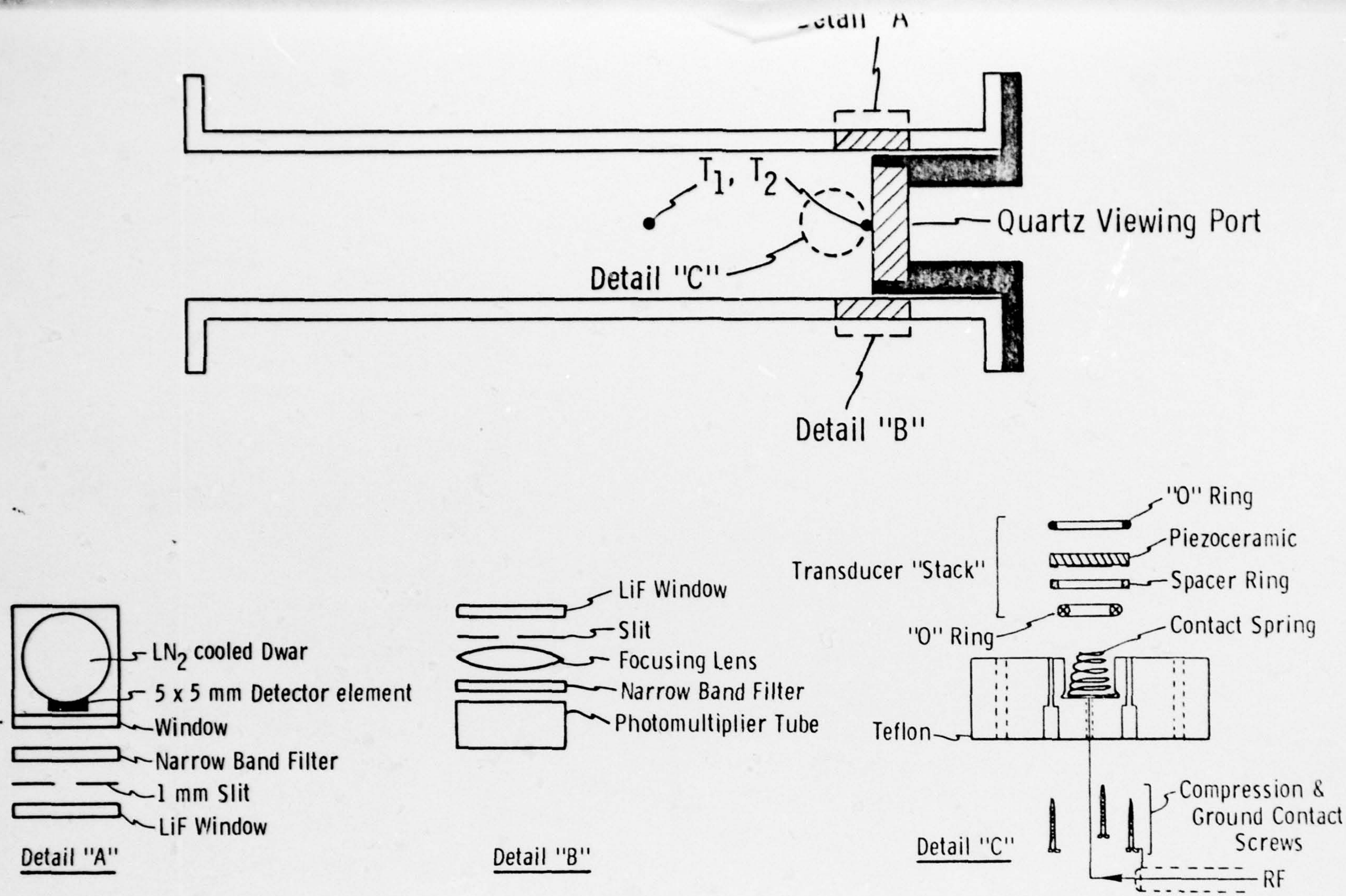
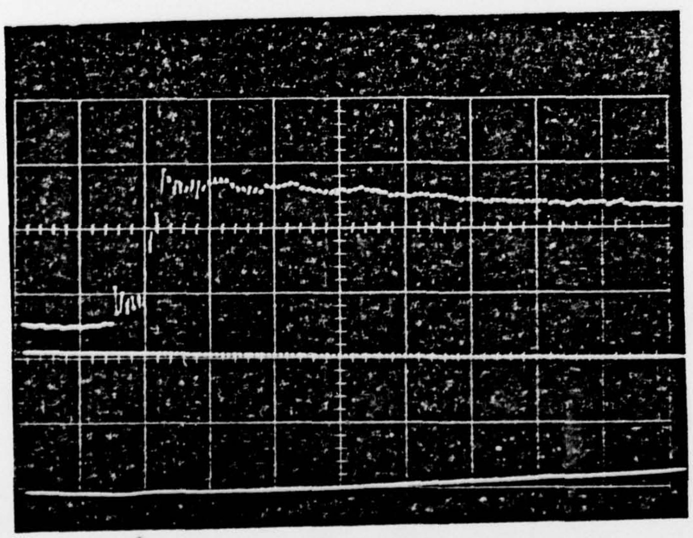



Figure 5. Detailed schematic of shock tube combustion zone.

The purpose of the first fully implemented nebulizer-coupled shock tube experiment was to ascertain a background RJ-5 vapor combustion visible and infrared emission level to be used as a reference for the nebulizer experiments. This was essential since it would otherwise be impossible to distinguish with certainty vapor from droplet combustion. In this initial experiment, fuel was placed on the surface of the transducer but not nebulized and a shock wave was generated through $O_2$ saturated with RJ-5 vapor. The Polaroid record of this experiment is shown in Figure 6. At the signal sensitivities chosen, no visible light was observed in the millisecond observation time but there was a small, but detectible, signal in the infrared which was attributed to the small amount of RJ-5 vapor combustion. The pressure profile is steady throughout the entire time period, suggesting that extensive energy-releasing reactions have not taken place.



$t_o$

Figure 6. Background RJ-5 vapor combustion at 1500°K. Lower trace: infrared emission from $CO_2$ (0.5 v/cm), middle trace, visible emission; upper trace, pressure profile. Sweep speed 100 μsec/cm, $t_o$ marks reflected shock arrival at observation station.

Following the above vapor combustion experiment, the experiment was repeated except that a small amount of the liquid fuel was nebulized to produce a low-density mist. The results of this experiment are shown in Figure 7. The appearance of both visible and infrared emissions shows clearly that mist ignition occurs after about 300 μsec followed by a slow droplet burning. The infrared emission prior to this point is again mostly due to the very rapid burning of the RJ-5 already in the vapor phase.

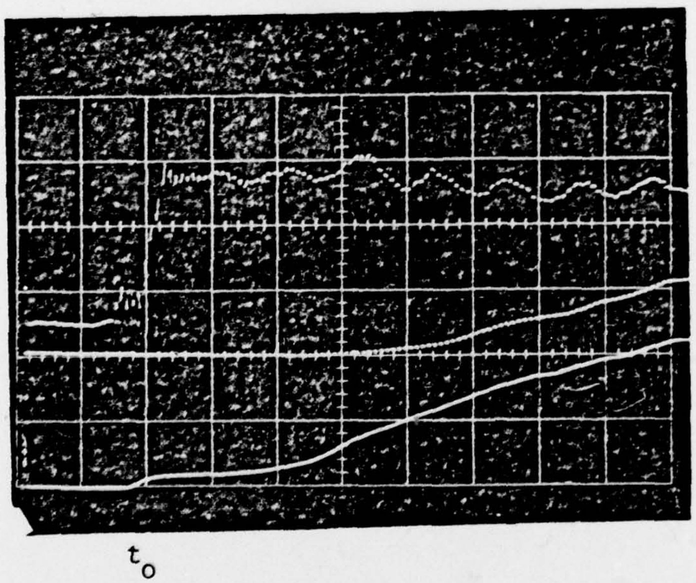
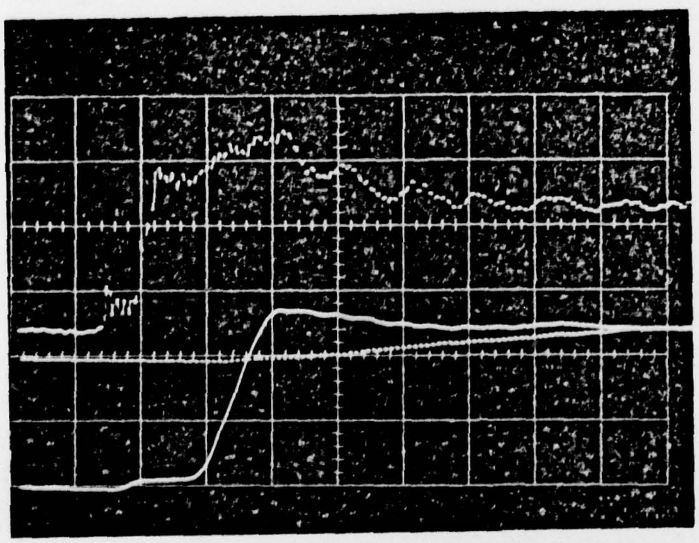


Figure 7. Nebulized RJ-5 combustion experiment at 1500°K. Lower trace: infrared emission from $CO_2$ (0.5 v/cm), middle trace, visible emission; upper trace, pressure profile. Sweep speed 100 μsec/cm, $t_o$ marks reflected shock arrival at observation station.

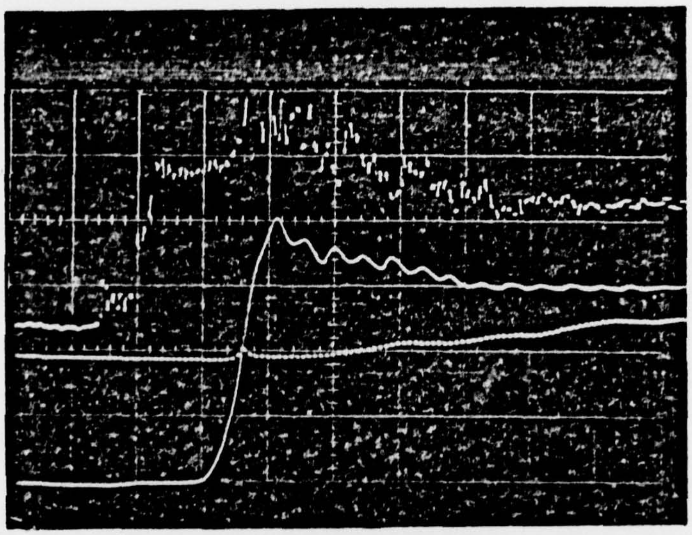
Figure 8 represents a repeat of the above experiment with a slightly higher concentration of fuel droplets. The driver pressure was also increased slightly in order to obtain a higher initial temperature aimed at driving droplet combustion to completion. This had the effect of decreasing the droplet ignition delay to about 100 μsec. The amount of $CO_2$ produced was significantly increased as is indicated by the increased infrared emission (note: the signal sensitivity for the infrared profile has been halfed). Also the signal leveled off, suggesting that combustion was complete. Furthermore, coincident with ignition was a pressure rise, indicating that a large amount of fuel was now burning.



$t_o$

Figure 8. Nebulized RJ-5 combustion at 1700°K. Lower trace: infrared emission from $CO_2$ (1 v/cm); middle trace, visible emission; upper trace, pressure profile. Sweep speed 100 μsec/cm, $t_o$ marks reflected shock arrival at observation station.

The above experiment was once again repeated except that the combustion chamber was saturated with RJ-5 droplets. As seen in Figure 9, $CO_2$ production was further increased and a large pressure pulse was observed suggesting extensive combustion was taking place.



$t_o$

Figure 9. Nebulized RJ-5 combustion at 1700°K. Lower trace: infrared emission from $CO_2$ (1 v/cm); middle trace, visible emission, upper trace, pressure profile. Sweep speed 100 μsec/cm, $t_o$ marks reflected shock arrival at observation station.

## Conclusions

The preceding series of experiments demonstrates unequivocally that the nebulizer-coupled-shock-tube technique has successfully initiated RJ-5 mist combustion. Furthermore, the infrared and pressure profiles should provide a good indication of the extent and rate of droplet combustion. The droplet ignition delay is measurable and decreases with increasing temperature and, as such, should provide useful information concerning the ignition processes. The visible emissions, when properly filtered may also yield a valuable insight into the combustion mechanism.

## Future Work

Now that the nebulizer-coupled-shock-tube is fully operational the remaining period will be concerned with the characterization of RJ-5 mist combustion. This will include measurement of ignition delays, burning rate as indicated by infrared and pressure profile, and a characterization of the visible emissions and the influence of droplet size, fuel/air ratio, the combustion pressure, and temperature on these parameters.

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1. M. T. McCall and J. M. Brupbacher, "Combustion Properties of High Density Fuels.", MML Quarterly Report, Contract No. N00019-76-C-0683, January 1977.

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